Lecture 8
Gas in the Galaxy

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(Notes by Paul Hickson)
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Gamma-ray emitting gas emanating from the galactic nucleus. Mellinger, Carretti, Bresser.

Distribution of the gas

The distribution of neutral hydrogen can be mapped by observing the 21 cm line. Molecular gas can be traced at millimetre wavelengths using CO lines.

One uses **kinematic distances** estimated from the observed radial velocity of the line and the galactic rotation model.

Within the **solar circle** $(R = R_0)$, these lines are often **optically-thick** $(\tau > 1)$ and a correction must be made for absorption.

Outside the solar circle, the distance to the emitting regions that is inferred from their radial velocity depends on the assumed galactic rotation curve $V(R)$.

X-rays are observed from tenuous hot gas at about 10^7 K. This gas cannot be bound to the Galaxy and must be escaping as a "wind".

Gas distribution.

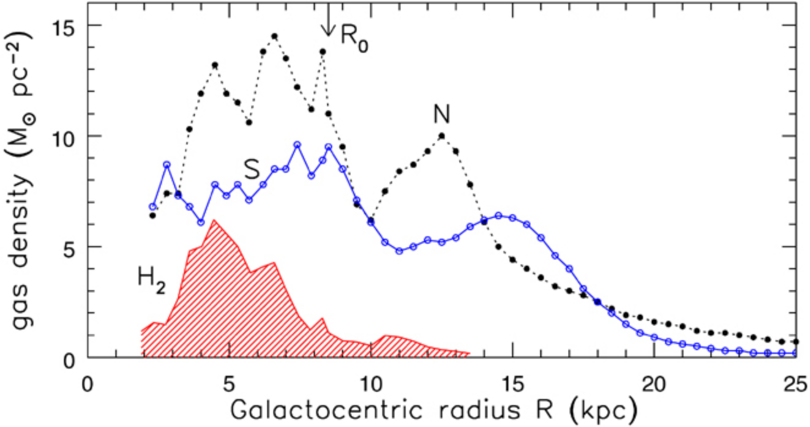


Fig 2.22 (Burton, Dame) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Surface density of neutral hydrogen (dots) and molecular hydrogen (shaded).

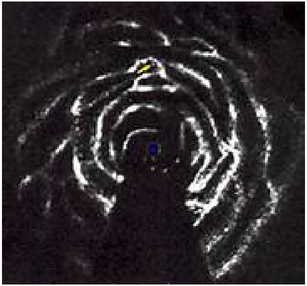
Gas distribution

The HI gas mass is estimated to be about $4 - 8 \times 10^9 M_\odot$ with about half of it inside the solar circle.

The mass of molecular gas (H_2) is about half the HI gas mass and it is concentrated in a ring of radius 4 kpc.

Dense molecular gas, and young stars, are concentrated in **spiral arms**. The Sun lies near one of these, the Sagittarius-Carina arm.

The **pitch angle** of the Galaxy's spiral arms is about 10°, which is typical of an Sbc galaxy.



21 cm map of the Galaxy. The position of the Sun is marked with an arrow.

Gas distribution

In the central 3 kpc of the disk, atomic and molecular gas lies in a disk that is tilted $10^\circ - 20^\circ$ to the plane of the galaxy. the gas clouds appear to be moving in elliptical orbits. This is consistent with a bar-like central bulge.

The central 200 pc contains more than $10^7 M_\odot$ of molecular gas (10% of the total for the Galaxy), which is actively forming stars.

Clouds of HI can also be seen at high galactic latitude. Many are **high-velocity clouds** falling towards the plane of the galaxy at over 100 km/s.

Some of this is infalling from beyond our galaxy. Some of it may be gas ejected by supernovae now falling back.

Physical conditions

There are at least three distinct phases of gas that coexist:

- cool gas - $T \lesssim 80$ K, $n_{\mathrm{H}} \sim 3 \times 10^7$ m^{-3}, typically found in dense molecular clouds
- warm gas - $T \sim 8000$ K, $n_{\mathrm{H}} \sim 3 \times 10^5$ m^{-3}, a mix of neutral and ionized gas
- hot gas - $T \sim 10^6$ K, $n_{\mathrm{H}} \sim 2 \times 10^3$ m^{-3}, highly ionized

The warm gas is created by UV photons from hot young stars, formed in a molecular cloud. The photons photo-dissociate the molecular gas and ionize it to create an HII region. This gas expands, pushing outward through the molecular cloud.

The hot gas is produced by supernovae explosions.

Cosmic rays

The galaxy is permeated by weak magnetic fields, with a typical strength of $\sim 0.5nT$ (about 10^{-5} of the Earth's magnetic field strength)

In supernova explosions, the magnetic field is swept up and carried outward by the ionized (and highly-conducting) gas.

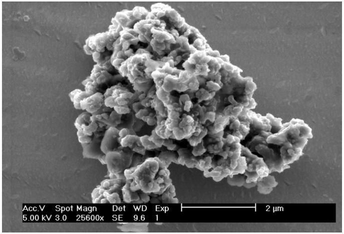
The moving magnetic field creates an electric field that accelerates charged particles such as protons and ions, to nearly the speed of light. These high-energy particles form the bulk of the **cosmic rays** that are observed on Earth.

Electrons are also accelerated, and radiate in the form of synchrotron radiation which is observed by radio telescopes.

Dust

Cool interstellar gas contains ~ 1 dust grain per 10^{12} hydrogen atoms, or about 1 grain per 10^6 m^3. The dust makes up about 1% of the mass of the interstallar medium.

This dust absorbs nearly half of the UV and optical light emitted by stars. This energy warms that grains which radiate in the infrared.



A large dust grain (~ 4 um).

In thermal equilibrium, as much energy is radiated as is absorbed, so the Galaxy's IR luminosity is comparable to its optical/UV luminosity.

The typical sizes of dust grains are $\lesssim 0.3$ um.

Dust

Dust grains consist mosly of magnesium and iron silicates, produced in the atmospheres of red giant stars. Also, carbon is found, in amorphous form, or as graphite.

In cool dense clouds, dust grains may be coated coated by ices of water, methane and ammonia.

Dust grains are believed to catalyze the formation of molecular hydrogen, increasing its formation rate by a factor of $\sim 10^8$.

About 10% $-$ 20% of the dust mass is believed to be in the form of organic molecules called **polycyclic aromatic hydrocarbons** (PAHs), containing as many as 100 carbon atoms.

Large grains typically have $T \sim 30$ K and produce radiation that peaks at a wavelength of about 100 um. Small grains ($\lesssim 10$ nm) can reach temperatures $\gtrsim 100$ K and radiate at shorter wavelengths (~ 30 um).

PAHs have many vibrational transitions in the $3 - 20$ um region.

Infrared spectrum.

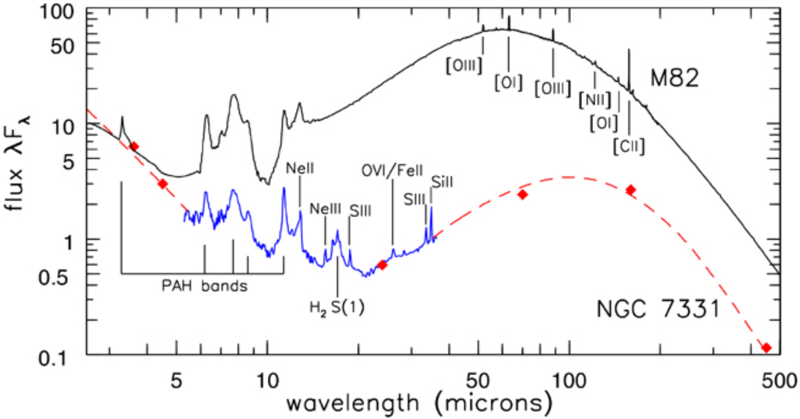


Fig 2.24 (Smith et al., Lagache) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

IR spectrum of NGC 7331, a galaxy similar to the Milky Way.

Recombination

In the interstellar medium, there is a balance between ionization and recombination

The recombination rate depends on the temperature, and the square of the electron density - why?

$$\frac{dn_{\mathsf{e}}}{dt} = -\alpha(T_{\mathsf{e}})n_{\mathsf{e}}^2,$$

where

$$\alpha(T_{\mathsf{e}}) \simeq 2\times10^{-19}\left(\frac{T_{\mathsf{e}}}{10^4\ \mathsf{K}}\right)^{-3/4}\mathsf{m}^3\mathsf{s}^{-1},\ (5000\ \mathsf{K} \lesssim T_{\mathsf{e}} \lesssim 20000\ \mathsf{K}).$$

Here T_{e} is the "electron temperature", the temperature corresponding to the typical electron energy ($E \simeq kT$).

The recombination time, $t_{\mathsf{rec}} = n_{\mathsf{e}}/|dn_{\mathsf{e}}/dt|$ is $\sim 10^3 - 10^6$ yr.

Cooling time

The typical kinetic energy, per unit volume, of the gas is

$$K \simeq \frac{3}{2}nkT$$

The rate at which the gas radiates energy is proportional to

$$L \propto n^2\Lambda(T),$$

where Λ depends only on temperature. Therefore, the cooling time

$$t_{\text{cool}} \propto \frac{T}{n\Lambda(T)}$$

For $T > 10^7$ K, the gas cools primarily by free-free radiation. For $T < 10^7$ K, almost all of the cooling is due to transitions in elements heavier than hydrogen and helium.

Luminosity and cooling time of the gas.

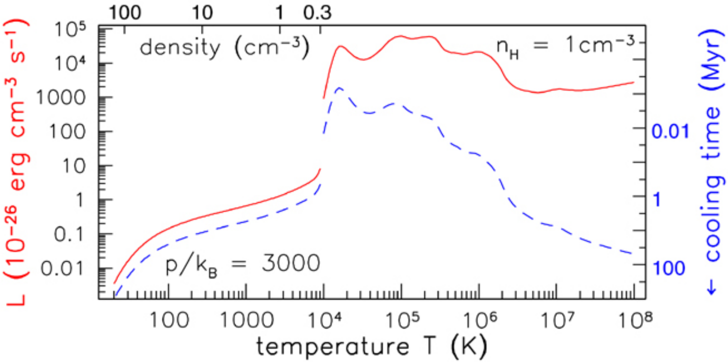


Fig 2.25 (Hensler, Wolfire) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

For gas of solar composition, luminosity L , from each cubic centimeter (solid curve), and cooling time t_{cool} (broken curve). Above 10000 K the gas is optically thin, and $L = n^2\Lambda(T)$. Below 10000 K the thermal pressure $p/k = 3000$, and cosmic-ray and ultraviolet fluxes are as measured near the Sun; we set $N_{\mathrm{H}} = 10^{19}\mathrm{cm}^{-2}$, so almost all H is atomic.

Heating

The diffuse hot gas is heated by shock waves from supernovae, typically every few million years.

The warm gas is heated by photoionization, and the cool gas is heated by contact with the dust grains, which absorb photons.

In dense molecular clouds, the main source of heat is cosmic rays. Infrared light also warms the dust grains, preventing them from cooling below $\sim 10K$.

Gas clouds have random motions, typically ~ 10 km/s, and sometimes collide. Such collisions are supersonic and create shock waves which heat the gas.

Roughly equal energy is contributed to the gas by collisions, magnetic fields and cosmic rays. This is because energy is continuously transferred between cloud motions, magnetic fields and cosmic rays which results in a rough **equipartition** of energy.

Jeans instability

Gravity will cause a cloud of density ρ and temperature T to collapse if its diameter exceeds the **Jeans length**

$$\lambda_{\mathsf{J}} = c_{\mathsf{s}}\sqrt{\pi/G\rho},$$

where c_{s} is the sound speed, $c_{\mathsf{s}}^2 = kT/\mu m_{\mathsf{H}}$.

Equivalently, it will collapse if its mass exceeds the **Jeans mass**

$$M_{\mathsf{J}} = \frac{\pi}{6}\lambda_{\mathsf{J}}^3\rho \simeq 20\left(\frac{T}{10\ \mathsf{K}}\right)^{3/2}\left(\frac{10^8\ \mathsf{m}^{-3}}{n}\right)^{1/2} M_{\odot}.$$

The fastest the cloud can collapse is the free-fall timescale

$$t_{\mathsf{ff}} = \sqrt{3\pi/32G\rho}$$

In reality the collapse is limited by the rate at which the gas can radiate the gravitational energy that is released.

Star formation

The galaxy has $\sim 10^9 M_\odot$ in molecular clouds that have densities of $\sim 10^8$ m^{-3} and $T \sim 10 - 20$ K. The corresponding Jeans mass is about $60 M_\odot$.

The collapse of clouds exceeding the Jeans mass should produce $\sim 100 M_\odot$ yr^{-1} of new stars. But, we observe a star formation rate of only $3 - 5 M_\odot$ yr^{-1}.

We conclude that something must slow the collapse, perhaps magnetic fields or turbulent motion.

Massive stars destroy the molecular cloud from which they formed, by photodissociation, stellar winds, and supernovae explosions. This cuts off further star formation in the region.

However, shock waves from supernovae can trigger the collapse of nearby gas clouds, producing new star formation.